



AEROSPACE INFORMATION REPORT

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(R) Information on Brake-By-Wire (BBW) Brake Control Systems

RATIONALE

The document has been reviewed and updated to the current state of the industry as part of a periodic document review schedule.

AIR5372A has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

Aircraft braking systems provide the pilot with a means of controlling the deceleration of the aircraft through the use of brake pedals, autobrake, and usually an emergency braking system. Before the advent of BBW systems, aircraft braking systems used hydraulically actuated brakes that were connected to the pilot's and copilot's brake pedals through mechanical cables, static hydraulic systems or linkages. In BBW systems, electrical sensors and wires replace the mechanical methods. Sensors are used to measure the pilot's command at the brake pedals and a Brake Control Unit (BCU) (sometimes referred to as a Brake System Control Unit (BSCU) or Electronic Control Unit (ECU)) sends out signals to electric or electro-hydraulic components that control the braking force. The other main functions that are provided by an aircraft braking system, independently of whether it is BBW or mechanically operated, are antiskid, autobrake, parking brake and emergency braking.

BBW systems are generally required to have a redundant means of applying brakes. These alternate braking or emergency braking systems usually rely on the mechanical levers and linkages that they seek to eliminate, increasing numbers of all electric BBW systems have been implemented over the past 10 years. These alternate braking or emergency braking systems usually rely on a dissimilar technology to alleviate common mode failure concerns.

In addition to the traditional electro-hydraulic brake actuation methods, completely electrically actuated (these are non-hydraulic systems that use electric motors, gearing and linear actuators) braking systems are also covered within this document.

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1. SCOPE

This SAE Aerospace Information Report (AIR) describes the design approaches used for current applications of aircraft Brake-by-Wire (BBW) control systems. The document also discusses the experience gained during service, and covers system, ergonomic, hardware, and development aspects. The document includes the lessons that have been learned during application of the technology.

Although there are a variety of approaches that have been used in the design of BBW systems, the main focus of this document is on the current state of the art systems.

1.1 Purpose

Although the designers and users of aircraft BBW systems are familiar with their functions, features, components, and limitations, there is no readily available documentation that describes the field in breadth. This document seeks to address this need by providing an overview of the current state of the art with respect to function, components, and issues.

The experience that has accumulated from existing BBW systems is presented as an aid to those who are embarking on the design of a new application or who are preparing specifications for a BBW system.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained (for example, refer to FAA FAR 25.735 or EASA CS 25.735; however, other regulatory agencies may apply).

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS483B	Skid Control Equipment
ARP862	Skid Control Performance
AIR1064	Braking System Dynamics
ARP1070	Design and Testing of Antiskid Brake Control Systems for Total Aircraft Compatibility
AIR1739	Information on Antiskid Systems
ARP1907	Automatic Braking Systems
ARP4754A	Guidelines for Development of Civil Aircraft and Systems
AIR5937	Information on Electric Brakes
AS8584	Brake Systems, Wheel, Military Aircraft

2.1.2 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA/DO160 Environmental Conditions and Test Procedures for Airborne Equipment

RTCA/DO178 Software Considerations in Airborne Systems and Equipment Certification

RTCA/DO254 Design Assurance Guidance for Airborne Electronic Hardware

2.1.3 FAA (Federal Aviation Authority) Publications

Available from www.acquisition.gov/far.

FAR 23.735 Brakes and braking systems

FAR 25.735 Brakes and braking systems

2.1.4 EASA (European Aviation Safety Agency) Regulations

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Cologne, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

CS 23.735 Brakes and braking systems

CS 25.735 Brakes and braking systems

3. FUNCTIONS AND REQUIREMENTS

3.1 General Requirements

The requirements for a BBW system should specify safety, functionality and performance parameters. The typical functions of a manned vehicle BBW system are manual brake pedal control, autobrakes and antiskid. Also, some form of alternate, parking, and/or emergency brakes are usually included in order to meet safety or operational requirements. (For example, an alternate 'park/emergency' brake may be part of the architecture to lower the criticality and cost of software from RTCA/DO-178 Level A to Level B.) Performance requirements include system response, braking efficiency (including the method of measuring efficiency), stability, reliability, and degraded operation. Reliability includes consideration of the level of redundancy and system separation needed to comply with customer requirements and regulations.

For brake by wire control, careful consideration needs to be given to failure modes within the brake control system that could result in applying braking when not commanded, i.e., 'uncommanded' braking. Uncommanded braking is often an unacceptable failure mode, and the system must be engineered properly to avoid this failure mode. (Uncommanded braking that occurs on takeoff is usually considered a catastrophic event.)

3.1.1 Unmanned Vehicles

In unmanned vehicles, many of the same functions exist as manned systems. However, brake pedals are replaced by computer commands and those commands can come from a human external to the vehicle or autonomously. Although comfort issues (ergonomics) do not apply, differential control is more important as are airframe dynamics. Without a pilot in the loop, who is actually seated in the aircraft, dependence on sensors for feedback control becomes much more important. Although the aircraft lacks a crew and passengers, safety levels have generally remained high.

3.2 Pedal Braking

Usually, the primary requirement for a BBW control system is to measure the pilot's and copilot's brake pedal displacement (left and right) and command a proportional brake clamping force to decelerate the aircraft. (On unmanned aircraft, commands come from autonomous control or ground-driven commands.) Pedal displacement is in the form of ankle rotation; therefore it is usually measured as an angular displacement in degrees, and the pedal force (pilot ergonomic feel) increases proportionally with increased braking levels. The pilot should be provided with a system that allows deceleration of the aircraft in a smooth and continuous manner by applying the brake pedals. The system should respond to the pilot's inputs based on the perception of aircraft deceleration in a way that feels natural. In order to close the loop between the pilot's intent and the response of the aircraft in a proportional manner, the BBW system design must account for the non-linear natures of the system inputs and outputs. The basic ergonomics of pedal force and travel, and the relationship between brake input, clamping force and output torque must be well understood. Also, the same pedals that apply braking are used for rudder control. The kinematics of the pilot's and copilot's rudder and brake pedals must assure minimal side effects when operating either or both mechanisms.

Differential braking where the right brake pedal controls the brakes on the right side of the aircraft (right main landing gear brakes), and the left pedal controls the brakes on the left side (left main landing gear brakes) is a basic requirement. This allows the pilot to control aircraft heading using the brake pedals. This is often referred to as differential braking. It may be required to include this feature to achieve acceptable ground directional control in the event of a nose wheel steering or rudder system failure.

3.2.1 Pedal Ergonomics

The brake pedal movement and resistance forces are configured to provide a feel proportional to the desired output, which is generally brake pressure. However, the physical sensation or feedback given to the pilot during pedal control is that of the resulting aircraft deceleration forces. The use of brake pedal position to generate the input command is typically a carryover from mechanical actuation methods, such as master cylinders and hydraulic brake metering valves, where the stroke is an inherent part of the control mechanism.

As the confidence and comfort level with BBW system ergonomics has been proven, the trend has been to reduce overall pedal travel and forces to allow easier actuation. Aircraft brake pedal ergonomics are independent to motion of the rudder pedal, which translates fore and aft carrying the brake pedal with it. The rudder pedal is normally operated through leg motion, while the brake pedal or "toe (ankle) brake" is applied by rotating the foot about the ankle joint. This approach limits the forces and range of motion that can be comfortably and controllably applied. In contrast, ground vehicles use "hanging" type pedals that allow much easier operation because the brakes are applied by pushing forward with the leg.

The level of resistance that the brake pedal provides to the pilot as a function of pedal stroke is referred to as "feel." Usually, pedal feel will be set up to emulate conventional systems that provide an increasing level of resistance as the pedal is rotated through a stroke of up to 20 degrees. However, there are some systems where very little stroke provision is made and pedal forces are the predominant parameter for control. Various ergonomic specifications and experience on simulators and in-service systems provide guidelines for pedal curves that effectively match pedal force and position for optimal feel. Section 6.1.1 lists the lessons learned on brake pedal operating characteristics. Figure 1 shows the consensus of the most recent experiences with pedal ergonomics, which also forms the basis for similar updates in AS8584.

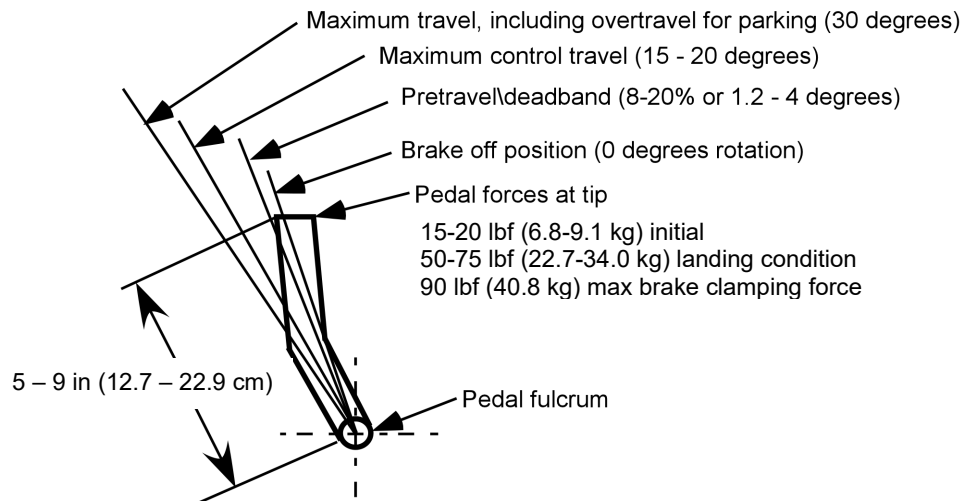


FIGURE 1 - BRAKE PEDAL ERGONOMICS

3.2.2 Pedal Laws

The relationship between pedal position or force and brake clamping force is defined by a “pedal curve” or “pedal law.” The slope of the curve represents the gain of the brake pedal system at any point on the curve. The goal of the pedal law design is to enable control of vehicle deceleration in a predictable and proportional fashion. If a pedal law is directly configured for deceleration, as opposed to the more conventional brake clamping force (or hydraulic pressure) control, then attention should be given to providing predictable feel and directional control as well as deceleration. The selection of an optimum pedal law requires the designer to have a good empirical knowledge of brake behavior and pilot ergonomics. This challenging area, as much art as it is science, has been the subject of continued discussion and debate. Historically, most systems have evolved with a ‘segmented’ (sometime referred to as non-linear) curve where low initial gain is used at low pressures when braking levels are insufficient to initiate skids. Antiskid activity can result in sudden large clamp force reductions that require the metering system to have a high gain in order to respond promptly. Non-linear-gain pedal curves have proved helpful in controlling torque-sensitive brakes.

The relationship between pedal travel, pedal force, and brake clamping force can be configured at the pedal input device for the desired gain relationship, and the gain and curve can be tailored in the control circuits of the BCU. Alternatively, the hydraulic valves can be configured to provide non-linear gain characteristics as shown in Figure 2. The electrical control circuits can be tailored for optimal gain characteristics more readily than the pedal transducer. The level of torque produced by a brake in response to a given brake clamping force varies greatly with the design, lining (brake) material used, physical condition, humidity factors, usage and temperature of the friction elements. In addition, the slope of the brake clamping force versus brake torque curve varies with speed. Since brakes are generally designed for maximum energy and minimum coefficient conditions- at low speeds and light clamping force levels, the change in torque for a given clamping force increment tends to be larger than that produced at high speed and high clamping force. The low speed region of pedal control is also called “taxi braking”, where aircraft behavior depends primarily on system and pilot interaction for smooth control. The clamping force onset should be as smooth as possible, especially with carbon brakes with their high torque gain at various brake temperatures. At brake-metered pressures above roughly one third of system pressure, the gain can be increased continuously or in two or more linear gain changes to allow full clamping force to be achieved rapidly when necessary. Step changes in brake clamping force may need to be avoided. Pedal curves and control laws that fail to account for these known non-linear relationships lead to complaints of brake sensitivity or “grabby brakes” from pilots.

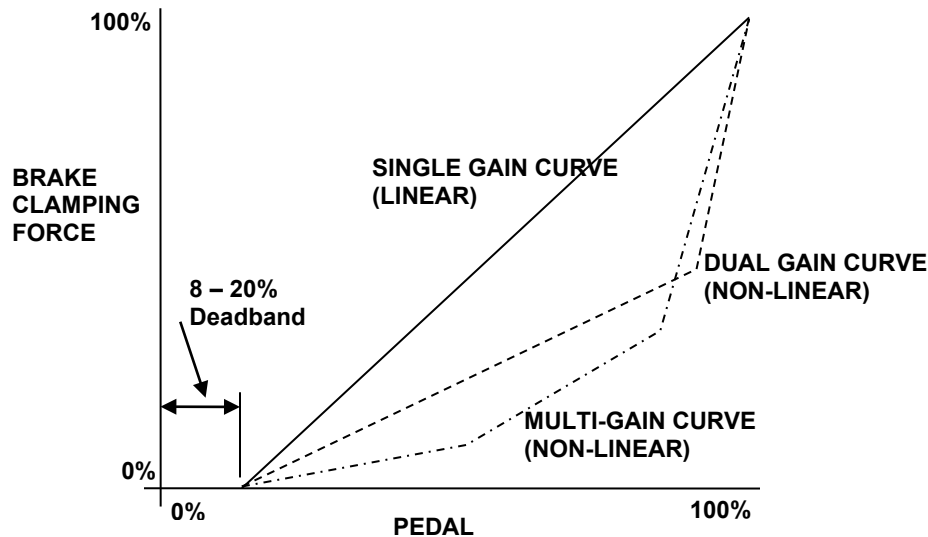


FIGURE 2 - BRAKE CLAMPING FORCE VERSUS PEDAL POSITION

3.3 Antiskid Function

The antiskid function is an essential feature of the brake control system (refer to AIR1739, ARP1070, ARP862, and AS483B for more information and regulations FAR 23.735, 25.735, CS 23.735, and CS 25.735). Control of the aircraft during braking cannot easily be achieved without antiskid protection when the nominal torque/drag output is greater than the tire-runway can support due to the characteristics of ice, rain, or any contamination. In addition, the inclusion of an antiskid system significantly improves stopping efficiency and cornering capability, and protects against hydroplaning, wheel lockup and tire skid-through. An antiskid system measures the speed of each wheel and uses the information to reduce the brake clamping force to the brake of any wheel that is on the 'verge' of skidding. Antiskid systems are usually considered to be 'passive' in that they can only reduce brake clamping force and cannot increase clamping force to a level above that commanded by the pilot pedal inputs or autobrake commands.

The antiskid function in a BBW system can be integrated into the system since it can be provided by the basic BBW control elements. The antiskid control algorithms can be implemented in the BBW BCU and control can be provided through the BBW control valve. Usually an Electro Hydraulic Valve (EHV) is associated with each main wheel's brake; however in some cases a single valve may control multiple brakes – as in paired wheel control braking. This may be in normal mode or in a degraded mode of operation. In an electrically actuated braking system, control is provided by the BBW BCU modulating the position or force commands to the Electrical Mechanical Actuators (EMAs).

3.3.1 Skid Control

Modern antiskid systems measure the speed of the wheel that is being braked and compares it with the synchronous speed. The synchronous speed is the speed that an 'unbraked' wheel, or some other reference source, would have.

When the brake is applied, the tire slips or may stretch at the point of contact with the runway, which has, for the wheel speed, the same effect as increasing the diameter of the tire. This causes a difference or 'slip' in measured wheel speed compared to synchronous speed. The antiskid control laws may be designed to detect the slip value or use the peak of the 'mu-slip curve' at which the tire has stretched to the point where it actually reduces adhesion with the runway surface and begins to go into a skid. The control system provides a brake clamping force reduction signal to the brake control valve or EMA to keep the wheel on the verge of a skid so that stopping efficiency and cornering capability are maximized. A fully modulating antiskid function can provide enhanced control for optimized braking performance on contaminated runways. The system seeks to maximize the use of available tire-runway friction coefficient (μ) regardless of aircraft speed, weight, or runway conditions, while optimizing tire wear. Sophisticated control laws, feedback of valve current, brake clamping force (or hydraulic force) and nonlinear computing elements are combined to result in an adaptive control system.